Ship Wake Detection in Speckle Noise using a Modified Hough Transform

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ABSTRACT

50 // Multiplicative speckle noise is a major feature of Synthetic Aperture Radar (SAR) images of ocean surfaces. Its effect is to give an image a "grainy" appearance often masking features of interest. The objective is to extract the characteristics of wake-like signals of low signal-to-noise ratio in such images. The approach taken is to consider the wakes as being composed of a sum of lines and to analyse them using the Modified Hough Transform (MHT), which places the average value of the points on a line in Cartesian co-ordinate space at that point in polar co-ordinate space which defines the line. The MHT method consists of two steps: first, possible wake-like signal regions are located and second, a statistical confidence level is determined for the wake-like signal that has been found. // Suppose the first stage has been performed and a signal-like region has been approximately located, then, for the cases studied, it was found that no more than a doubling of the maximum signal amplitude is required to achieve the same statistical confidence in MHT detection as would be achieved using the optimum matched filter. For illustration an example is presented where the signal is undiscernible in the image by eye; however, it is recoverable using the MHT method.

KEYWORDS

Hough Transform, Synthetic Aperture Radar, image processing, signal detection.

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1. INTRODUCTION

Multiplicative speckle noise is a major feature of Synthetic Aperture Radar (SAR) images of ocean surfaces. Its effect is to give an image a "grainy" appearance often masking features of interest [1]. The objective in this paper is to describe techniques that may be employed to detect wake-like signals of low signal-to-noise ratio in SAR images.

When rough surfaces are illuminated by coherent radiation whose wavelength is of the order of that typical of the surface roughness, interference of the reflected waves produces a noise called speckle [2,3]. The characteristics of this noise[3] have been studied extensively and various digital processing methods [4,5,6] have been suggested to remove or minimise its effects assuming high signal-to-noise ratio. As a result of their work in this field, Lem and Nawab[4] have observed that: " in general there is no known algorithm which effectively enhances images degraded by additive random noise at a very low signal-to-noise ratio". Since by taking the logarithm of the image intensities multiplicative noise becomes additive, this conclusion is valid for the case considered herein.

This paper is restricted to methods applicable to a particular problem: extraction of wake-like signals from images corrupted by speckle noise. The signals will be either barely discernible or not discernible by the naked eye. Rather than image enhancement, methods are proposed which detect the signal and/or extract its main features.

The properties of speckle noise are reviewed in Section 2. As well, a model for wake signals is proposed. In Section 3 the problem to be considered is defined. A Modified Hough Transform (MHT) technique is described in Section 4 and is applied to a simulated wake corrupted by speckle noise. A comparison of the MHT method and optimum matched filter (MF) for this above example is carried out. The MHT is shown to be potentially a useful method, which does not require the degree of a priori knowledge necessary to the application of the MF. Section 5 contains a summary of the results.

2. SIGNAL AND NOISE MODEL

2.1 Signal Model

SAR observations of ship wakes have been separated into three general classes: surface waves, turbulent wakes and internal ship-wave wakes[7]. Figure 1 is an example of a surface wave wake. From an examination of many ship wakes it has been observed that [7,8]:

(1) There are great variabilities in the observed images even within the three general classes. Some of the reasons for this are understood - the orientation of the wakes with respect to the SAR sensor has an influence as does ship and wind speeds and wind conditions.
(2) Ship wakes appear in SAR images as features which are linear or nearly so.
(3) A wake can have one or two observable "arms" with a relatively small angle between them.
(4) Each arm in turn is contained within a narrow angular region.
(5) Modulation can occur within the region of an arm.

A wake-like signal model has been constructed to include the above features and to serve as an ideal source for image analysis purposes (but it is not intended to be an explanative model). Figure 2 is an illustration of this model. As noted, the ship wake features are contained in an angular region, measured from the axis of symmetry, between θ_{min} and θ_{max}. The average of these values is denoted θ_{mid}. Observed values of θ_{mid} range between 3° and 20°. The number of cycles between A and B is a parameter (here it is one) and this is in turn modulated by a cosine taper. Here s(x,y) is the signal whose maximum wake amplitude is a and $|a| \leq 1$, thus $1 + s(x, y) \geq 0$.

2.2 Speckle Noise

Intensity distributions called speckle occur in many physical phenomena including SAR observations of the ocean surface. Its characteristics have been studied in some detail [3]. Those properities relevant to the sensing of ocean waves with SAR are summarized herein. Speckle noise is multiplicative, that is , the observed pixel intensity m (x,y) is given by

$$m(x, y) = n(x, y)(1 + s(x, y)) \qquad (1)$$

where n(x,y) is speckle noise, and s(x,y) is the signal. Speckle noise obeys an exponential distribution and is independent from point to point. The mean of an exponential random variable equals its standard deviation, and so, when a signal is present with amplitude s(x,y), the mean and standard deviation both become 1 + s(x,y). Hence, in regions where s(x,y) is positive, the image has more large values compared to areas where the signal amplitude is negative.

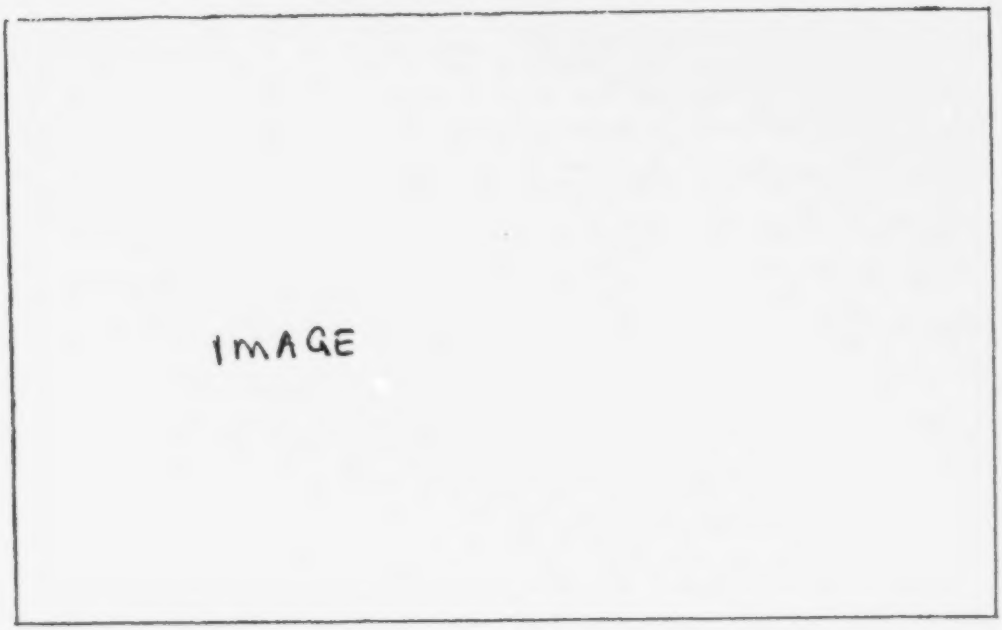
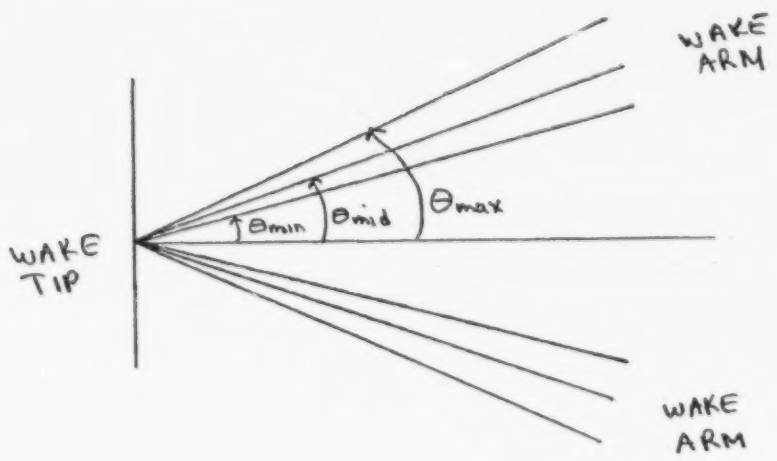


Figure 1 SAR L Band Digital Slant Range Image of a Surface Ship Wake, Dabob Bay, July 28, 1983. Processed by Environmental Research Institute of Michigan



Cross Section of the Model taken from A to B in the case of one modulated cycle

Figure 2 Wake-like Signal Model

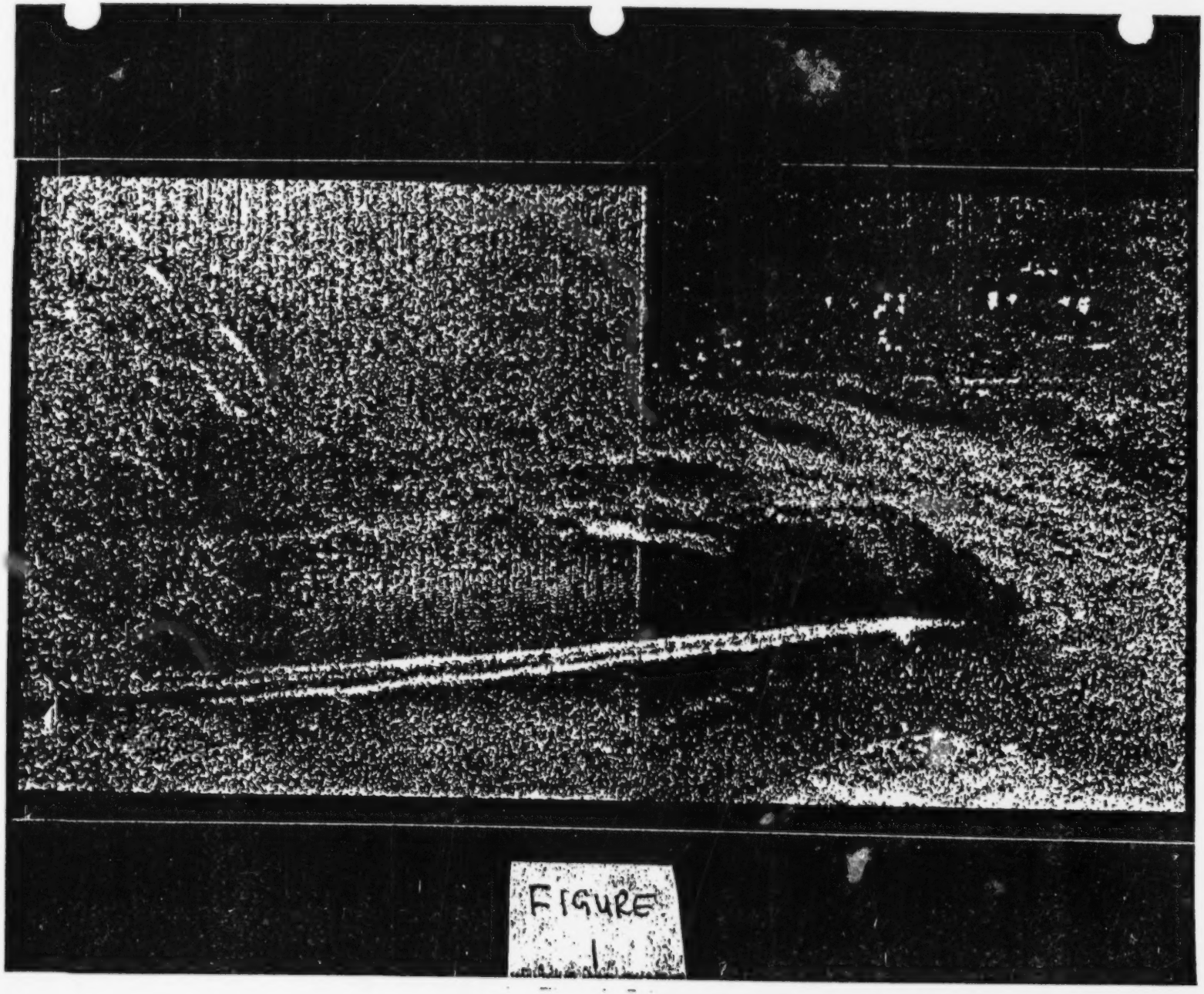


FIGURE 1

3. STATEMENT OF PROBLEM

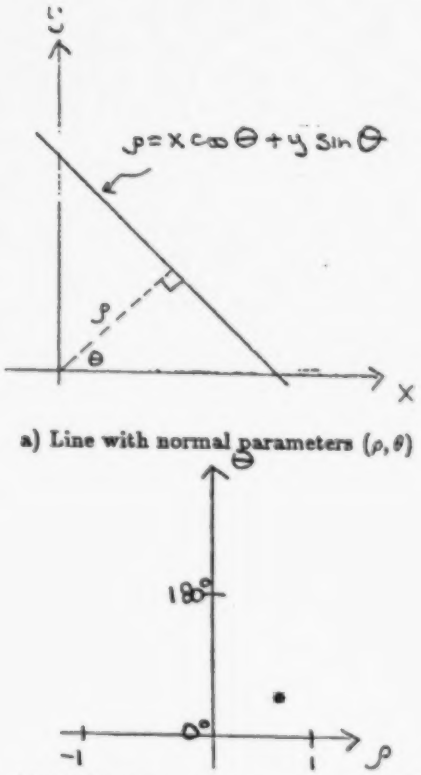
In the following the suitability of the MHT method is shown for the extraction of wake-like signals of low signal-to-noise ratios corrupted by speckle noise. The approach is a statistical one and statements are made concerning detection probabilities, probability to extract wake features, et cetera. Hence in the following, simulated signals and noise are used so that the signal-to-noise ratio can be controlled.

The data consists of digital images which for this paper are 512 by 512 pixels in size with 255 quantization levels. The idea is to generate the type of images produced when a SAR senses ocean surfaces. They are speckle noise only or noise and signal. By signal is meant some portion of any of the ship wake signals of section 2.1. That is, a ship wake is generated with a certain set of parameters over a large surface. Then a portion of the surface of digital size 512 by 512 is chosen. The only restriction on the portion of signal obtained is that the wake tip is NOT contained within the image, since for illustrative purposes, it is desired to have signals which extend fully over the image. The presence of a wake tip poses no problem other than restricting the length of the wake arm present in the image.

4. MODIFIED HOUGH TRANSFORM

4.1 Method - Step One

Integral transforms have been used effectively in image processing for a number of years[10]. The key idea of integral transforms with regard to signal-to-noise improvement is that features not prominent or possibly not even visible in the given image (that is the spatial domain) are identifiable in the transform domain. An inverse transform may then be performed on just the features so identified so as to yield signal enhancement. The Modified Hough Transform places the average value of the points on a line in Cartesian co-ordinate space at that point in polar co-ordinate space that defines the line. The line parameters are (ρ, θ) where ρ is the distance of the line from the origin and θ is the angle of its normal line with respect to the positive x axis. See Figure 3 and Pratt [10]. The power of the MHT is that the signal-to-noise ratio of lines in the transformed space is improved by a factor of $\sqrt{L}$ where L is the length of the line. It enables signals not visible in the Cartesian plane to be detected in the transformed space.



a) Line with normal parameters (ρ, θ)

b) Modified Hough Transform of the line of a)

Figure 3 A line and its Hough Transform

Consider a digital image whose intensity at integer location (i, j) is M(i, j). For a set of equally spaced angles, θ_K, and equally incremented distance values, ρ_e, $H(\rho_e, \theta_K)$, which is the average intensity of the image points on the (ρ_e, θ_K) line is calculated. Since for a given (i, j) and θ_K the distance ρ, equal to $i\sin(\theta_K) + j\cos(\theta_K)$, is not necessarily equal to an integer, linear interpolation is used during the determination of $H(\rho_e, \theta_K)$[11].

Figure 4(a) is an image of a wake-like signal (constructed as defined in Section 3) corrupted by speckle noise and Figure 4(b) is its MHT. The angle increments for the transform are one half degrees and the ρ increments are 1. Note that ρ can be positive or negative. As well, the display contains values for angles greater than π. It may be shown that $H(\rho, \theta + \pi) = H(-\rho, \theta)$.

The local maxima correspond to (ρ, θ) combinations of $(-26, 72°), (45, 76°)$and$(124, 79°)$; while the minima are at $(8, 75°)$and$(75, 78.5°)$. The five lines these points describe are displayed in Figure 5(a), superimposed on the signal-only image used in constructing Figure 4(a). It is observed that the main wake structure features - crests, troughs - are well estimated. Figure 5(b) is a reconstruction of

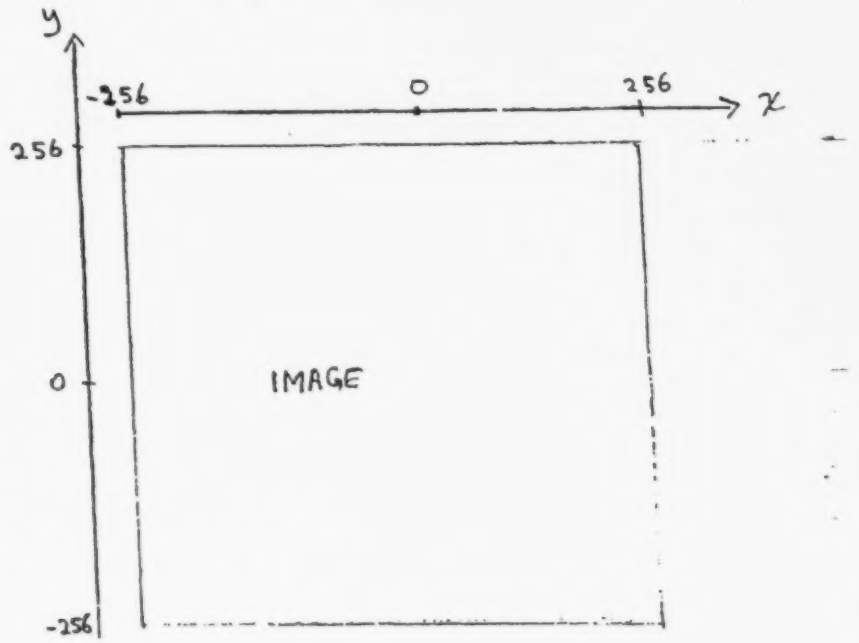


Figure 4(a) Wake-like signal with maximum signal amplitude .06 multiplied by unit mean speckle noise

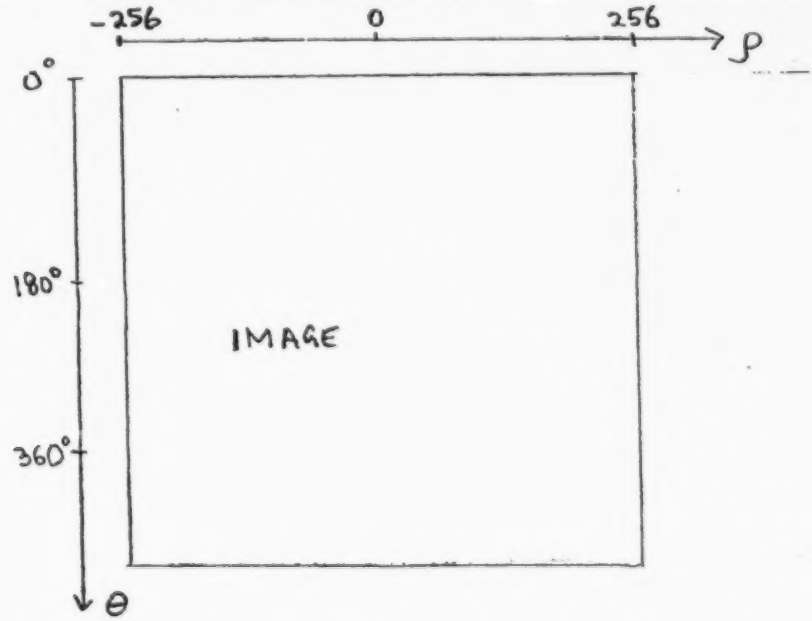


Figure 4(b) Modified Hough Transform of Figure 4(a)

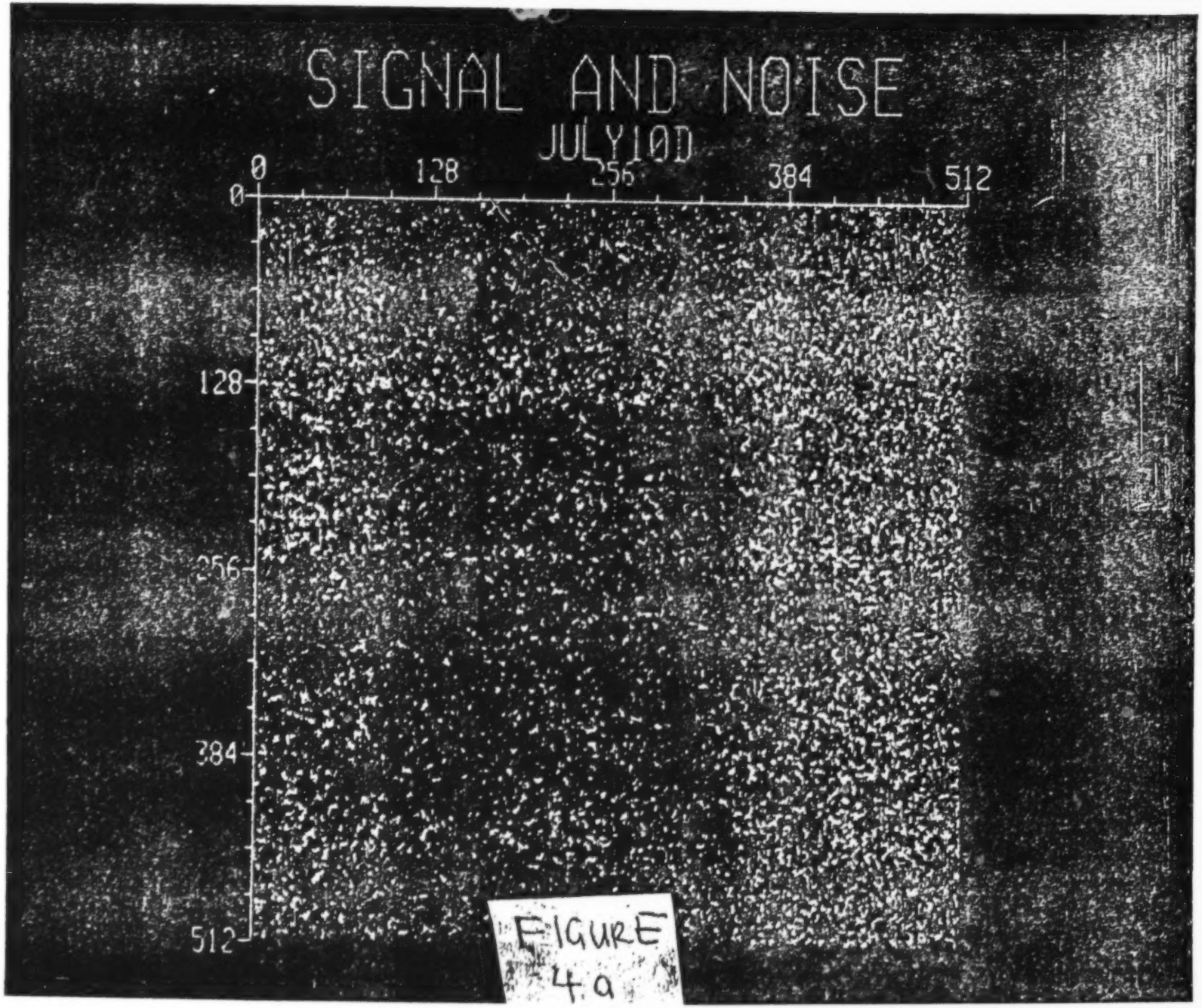


FIGURE 4.a

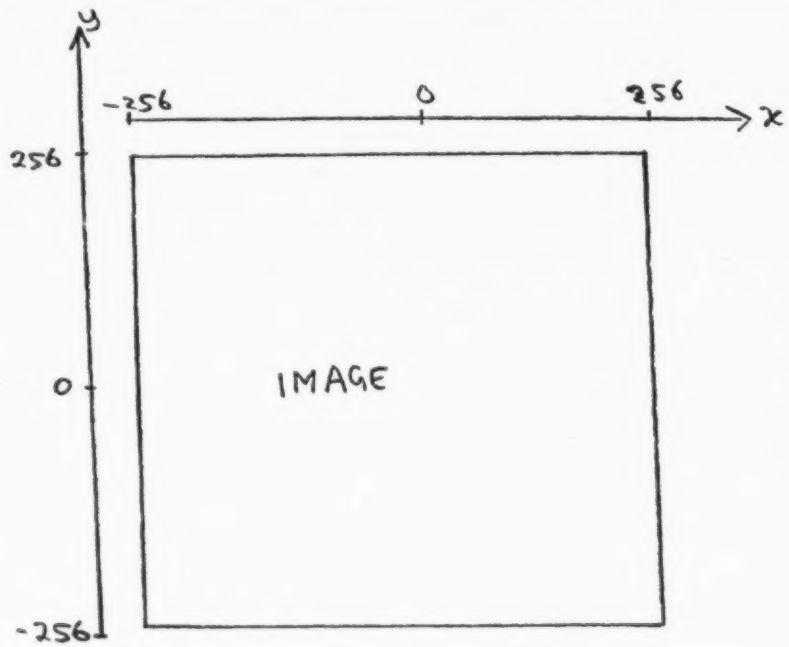


Figure 5(a) Crests and Troughs of wake-like signal of Figure 4(a) recovered by MHT method superimposed on noise free signal

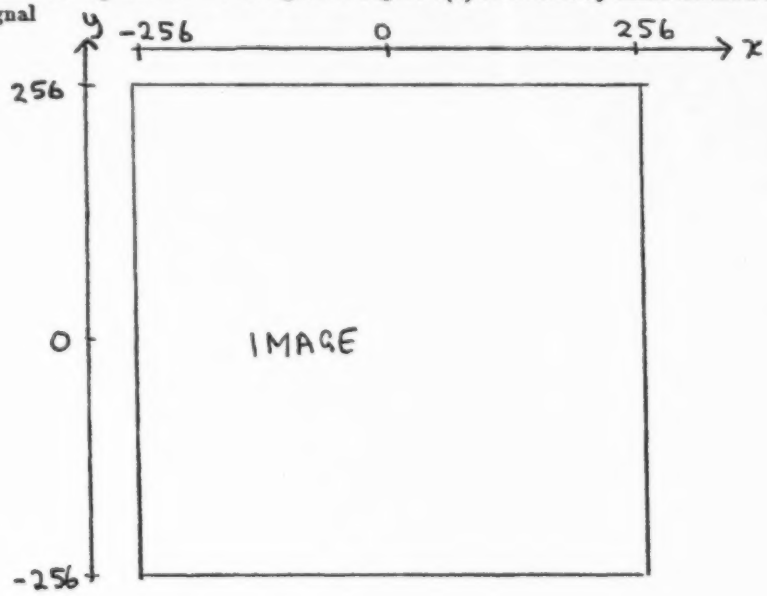


Figure 5(b) Reconstruction of wake-like signal using a reverse Hough Transform from the identified region of interest of Figure 4(b)

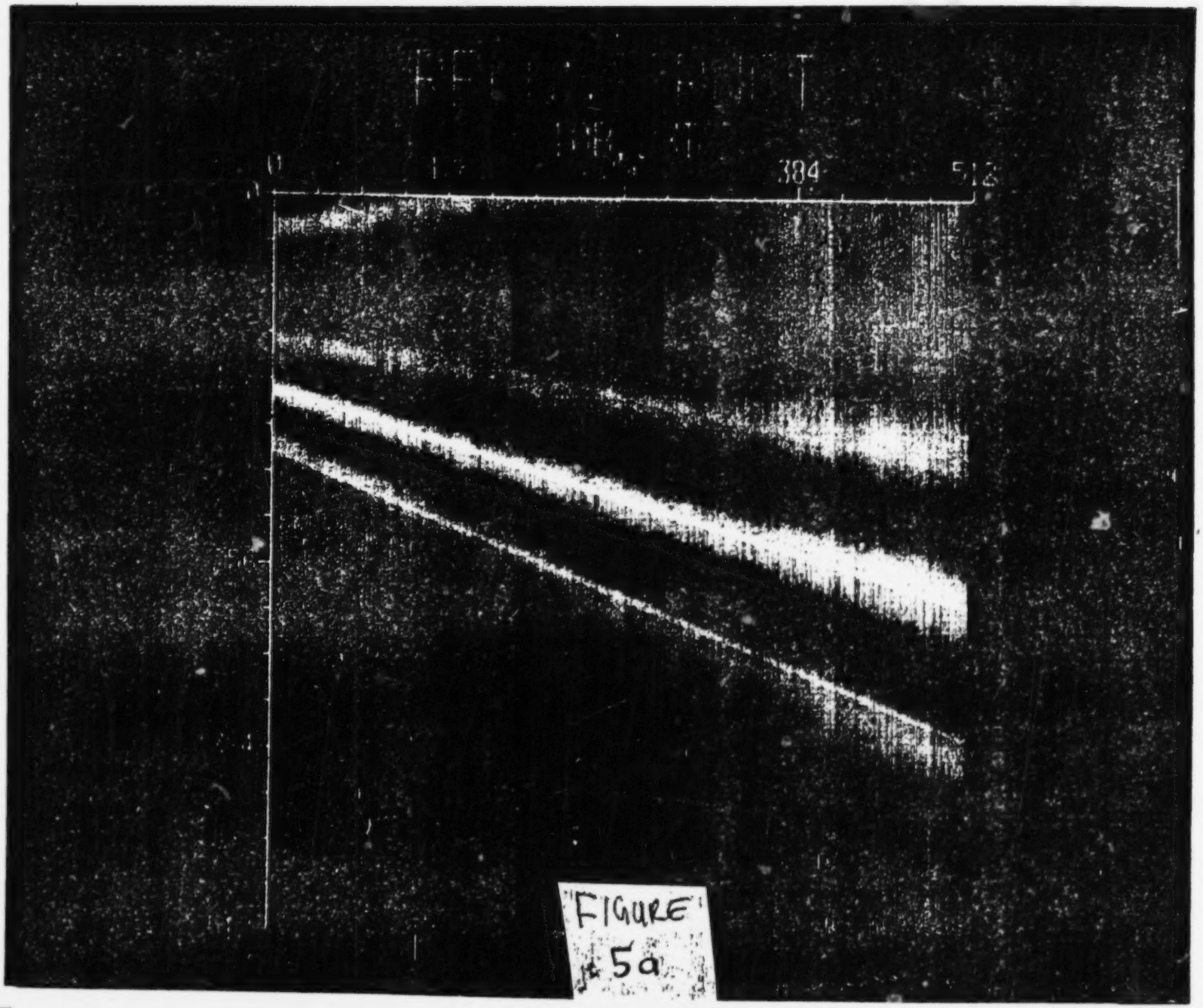


FIGURE
#5a

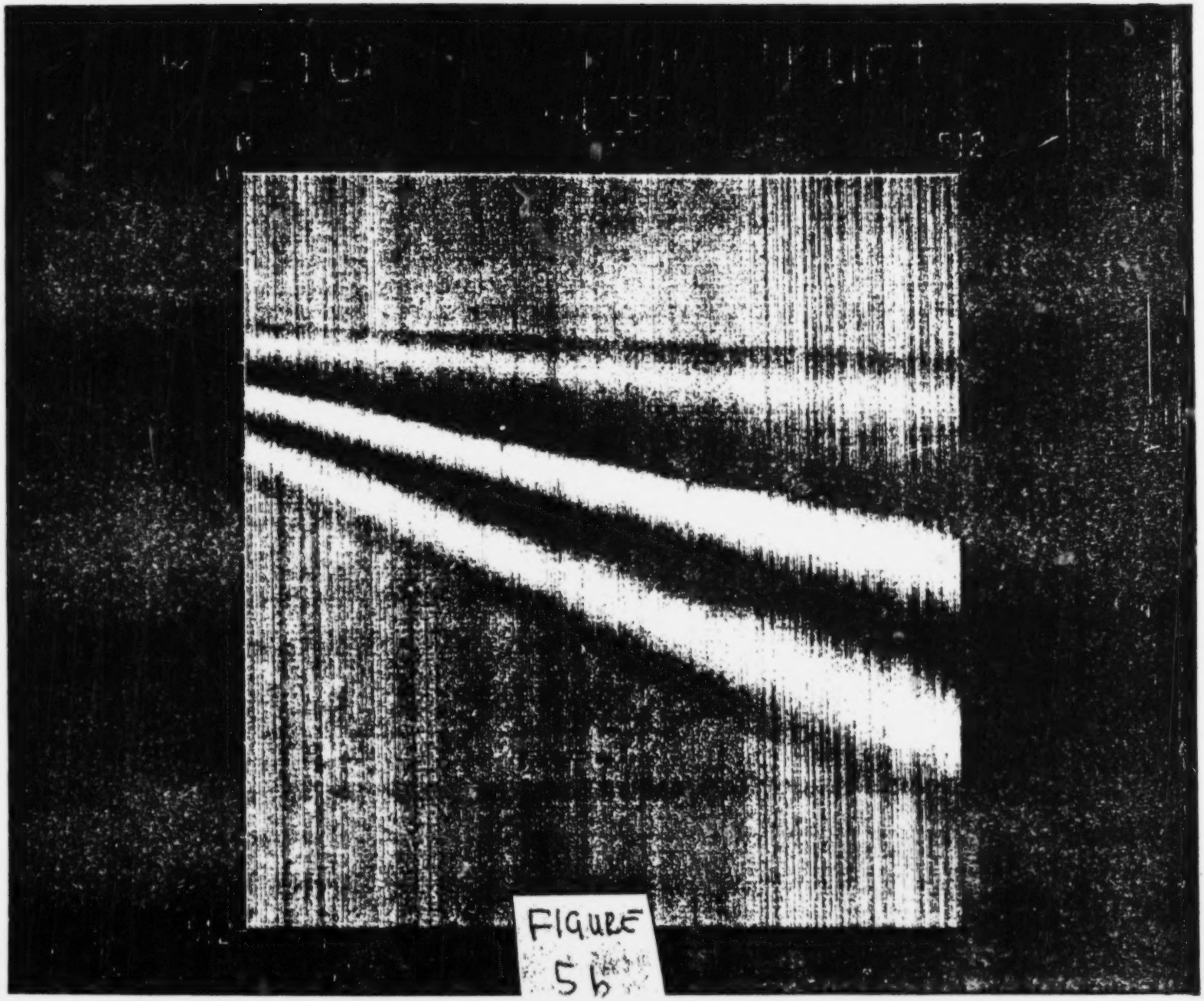


FIGURE 5b

the signal using an inverse Hough Transform of the above identified region of interest.

4.2 Method - Step 2

In this step the statistical significance of the wake-like region found at step one is determined, assuming that the presence of a signal causes the image to have regions different in mean value than the overall image. To begin, a calculation determines the number of normalized standard deviations by which that portion of the original image corresponding to a small neighbourhood about the line regions located at step 1 is different than the mean value of a region of noise only. Then, if this number of deviations is large it is accepted that a wake signal has been found and, if small, that there is noise only in the image.

For the previous example the portion of the original image corresponding to the region containing the high intensity lines and a typical small neighbourhood around them contains 21402 points and is 4.52 standard deviations above the population mean while the lower intensity lines and a typical small region about them contain 11480 points and is 4.68 deviations less than the sample mean. (The construction of a "small neighbourhood about the lines" is subjective. However the choice is not critical; any reasonable interpretation of the above yields regions with sample means which differ from the population mean by approximately the same number of normalised deviations.) The two regions may be considered as one which contains a set of points which differ from the population mean by 6.36 standard deviations. The probability that a noise only sample of this size differs from the population mean by this amount is 10^{-10}. With such a low probability that the region is noise only, it is concluded that a wake-like signal has indeed been located.

4.3 Comparison with Matched Filter

For received data m(x,y) a linear test statistic U is defined as

$$U = \left(\int_R \int m(x,y)t(x,y)dydx - \int_R \int t(x,y)dydx\right) / \left(\int\int t^2(x,y)dydx\right)^{1/2} \qquad (2)$$

where U depends on the weighting function t and region of integration R. For cases such as those considered herein, in which the number of pixel elements where the signal is non-zero is large and the signal-to-noise ratio is small, the probability of detection, PDET, is [12]

$$PDET = Q(Z_\alpha - DI) \qquad (3)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty exp(-x^2/2)dx$, α is the false alarm probability and $Q(Z_\alpha) = \alpha$. The quantity DI is called the detection index and is equal to $\int\int s(x,y)t(x,y)dydx / \left(\int\int t^2(x,y)dydx\right)^{1/2}$. The optimum detector, according to the Neyman-Pearson criterion, is the MF which sets t equal to s and R the region where s is non-zero. The MF detection index for the example is 10.

For template matching (TM), t is set to one for the region where the signal is positive (say R^+) and minus one where the signal is negative (say R^-). Then R equals $R^+ \cup R^-$ where $\cup$ denotes union. The TM detection index is 7.95, assuming the signal is known exactly.

The MHT may be viewed as adaptive template matching. At Step 1, possible signal-like features are found by visual inspection of the data's MHT. That is, regions are located in the spatial domain where the signal is believed to be positive and negative, say $\hat{R}^+$ and $\hat{R}^-$. Next, the TM statistic is calculated. If this quantity is above a certain threshold the hypothesis is accepted that a wake-like signal has been extracted; otherwise it is accepted that the data is noise only. For the estimated signal regions of the example the TM detection index is 7.0. Thus there is a slight loss in the DI for the example when the signal region is not known exactly. The TM test statistic for this region, as noted in section 4.2 was 6.36 standard deviations.

The detection index's for TM and MF depend only on signal amplitude. For the above case no more than a doubling of this amplitude was required to achieve comparable results using TM as compared to the optimum MF. This conclusion holds for other examples studied [11].

5. SUMMARY

This paper has considered the problem of extracting the main features of wake-like signals of low signal-to-noise ratio in multiplicative speckle noise. One example of such a wake which was barely not visible in the spatial domain was studied in detail. The MHT method was able to extract the signal. The method consists of two steps; the determination of a region containing a wake-like signal and then the calculation of the TM statistic for the region. Conditions under which the first step may be performed are least understood and are currently under investigation. For a number of cases examined, including the example above it was found that,

if the signal region can be approximately located, at most a doubling of the signal amplitude is necessary to achieve comparable performance using TM as compared to the optimum matched filter.

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